A

Project Report

On

Indoor Positioning Using UWB-IR Signals in the Presence of Dense Multipath with Path Overlapping

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Abstract:

This paper presents a method for positioning using ultra-wideband impulse radio (UWB-IR) signals that is robust in indoor environments characterized by dense multipath channel with path overlapping. Path overlapping effects arising from multipath in dense cluttered environments decrease the direct path resolution in time domain, and hence induce time-of-arrival (TOA) and angle-of-arrival (AOA) based positioning inaccuracy. To mitigate this problem, system design that is capable of resolving the closely-spaced multipath at low cost is of value. Our method yields the least-squares estimation of joint TOA and AOA with low computational cost. It is based on the spectral observation of beam forming, in which the path overlapping effect is mitigated using multipath-aided acquisition. The computational cost is reduced using in-band power spectrum and accurate initial estimations. The performance is verified both in IEEE 802.15.4a CM3 channel model and in a real environment. Simulation results in CM3 channel model show that the TOA and AOA estimation improvements on average are 2.4cm and 13.1o in the dense multipath scenario. Measurement in an indoor open hall environment shows that the AOA error decreases from 10.6o to 7.2o, and the TOA error decreases from 2.1cm to 1.9cm when the path overlapping effects are mitigated in the range of 21m.

Introduction:

• An indoor positioning system (IPS) is a network of devices used to wirelessly locate objects or people inside a building.
• UWB-IR is a excellent means for wireless positioning due to its high resolution capability in the time domain and it offers high data rate and low power consumption because of large bandwidth.
• The main purpose of this paper is to a method for indoor positioning using ultra-wideband impulse radio (UWB-IR) signals that is robust in indoor environments characterized by dense multipath channel with path overlapping.
• Path overlapping effects arising from multipath in dense cluttered environments decrease the direct path resolution in time domain, and hence induce time-of-arrival (TOA) and angle-of-arrival (AOA) based positioning inaccuracy.
• To mitigate this problem, our method yields the least-squares estimation of joint TOA and AOA with low computational cost.
• This paper is concerned with the dense multipath channel effect on joint TOA and AOA estimator design.
• To extract TOA from the signal, search for maximum correlation between signal and shifted version of it.
• AOA estimators using UWB-IR signals can be entirely based on time-difference-of-arrival (TDOA) between signals arriving at antenna elements in the receiver array.
• These TOA-based AOA estimators work with measurements of the baseband pulses and are thus lower in hardware complexity.
• The Cramér-Rao bound of TOA and AOA estimations is jointly derived from the probability density function (PDF) of the array signals.

**Theoretical Bound Derivation**

- A mobile with an antenna array receiver can locate itself with respect to the beacon by jointly estimating the TOA and AOA of the direct path. The UWB-IR ranging signal transmitted from the beacon can be given as,

\[
s(t) = \sum_{i=-\infty}^{\infty} u(t - iT_f)
\]

where \( u(t) \) is the UWB signal pulse shape with an ultra-short duration, and \( T_f \) is the pulse repetitive period.

- Considering \( L \) plane waves impinging on a \( N \)-element antenna array with \( L_e - L \) near-field perturbations, the time signal received at the \( e \)th antenna element can be expressed as,

\[
x^e(t) = \sum_{l=1}^{L} a_l s(t - \tau_l^o + \Delta\tau^e(\theta_l)) + \sum_{l=L+1}^{L_e} a_l^e s(t - \tau_l^e) + n^e(t)
\]

where \( \theta_l \) and \( a_l \) are respectively the AOA and amplitude of the \( l \)th plane wave. \( a_l^e \) and \( \tau_l^e \) denote the near-field path amplitude and time delay that are inconsistent
among the array elements. \( n^e(t) \) is assumed as the spatial white noise of double-sided power spectral density \( N_0/2 \).

**Antenna array: ULA and UAA**

- The TOA at the \( e^{\text{th}} \) antenna element is constrained by the antenna array geometry as,

![Diagram](image1.png)

**Figure : Contours, convex hull and convex defect points.**

![Diagram](image2.png)

**Figure : Contours, convex hull and convex defect points.**

- For the plane wave propagation, the TOA at the \( eth \) antenna element is constrained by the antenna array geometry as,
relative delay $\Delta \tau_e$ at the $e^{th}$ antenna element with respect to the TOA at the array geometric center $\tau^0$, where $r_0$ denotes the distance between sensors in the array, and $c$ is the speed of light.

- The probability density function (PDF) of the array received signals $x$ conditioned on the vector $\eta$ can be written as,

$$\ln p(x|\eta) = \sum_{e=1}^{N} \ln p(x^e|\eta)$$

- The Fisher information matrix (FIM) is defined as,

$$J(x|\eta; \eta_i, \eta_j) \triangleq -E\left\{ \frac{\partial^2 \ln p(x|\eta)}{\partial \eta_i \partial \eta_j} \right\}$$

- The Cramér-Rao bounds (CRB) for the direct path estimation $\tau^0, \theta_1$ and $a_1$ can be obtained by taking the inverse of the FIM,

$$\text{CRB} (\tau^0, \theta_1, a_1) = \left[ \left( A - \sum_{e=1}^{N} C_e B_e^{-1} C_e^T \right)^{-1} \right]_{3 \times 3}$$
Auto-correlation and cross-correlation functions of the source signal $s(t)$ and its time derivative $s'(t)$ are derived as,

$$\mathbf{A} = \begin{bmatrix} A^{(1,1)} & \cdots & A^{(1,L)} \\ \vdots & \ddots & \vdots \\ [A^{(1,L)}]^T & \cdots & A^{(L,L)} \end{bmatrix}$$

$$\mathbf{B}_e = \begin{bmatrix} B_e^{(L+1,L+1)} & \cdots & B_e^{(L+1,L_e)} \\ \vdots & \ddots & \vdots \\ B_e^{(L_e,L+1)} & \cdots & B_e^{(L_e,L_e)} \end{bmatrix}$$

$$\mathbf{B}_e^{(i,j)} = \frac{2}{N_0} \begin{bmatrix} a_i^e a_j^e \hat{R}_s (\tau_j^e - \tau_i^e) & a_i^e \hat{\dot{R}}_s (\tau_j^e - \tau_i^e) \\ -a_j^e \hat{R}_s (\tau_j^e - \tau_i^e) & R_s (\tau_j^e - \tau_i^e) \end{bmatrix}$$

$$\mathbf{C}_e = \begin{bmatrix} C_e^{(1,L+1)} & \cdots & C_e^{(1,L_e)} \\ \vdots & \ddots & \vdots \\ C_e^{(L,L+1)} & \cdots & C_e^{(L,L_e)} \end{bmatrix}$$

- Auto-correlation and cross-correlation functions of the source signal $s(t)$ and its time derivative $s'(t)$ are derived as,

$$R_s(\tau) \triangleq \int s(t)s(t - \tau)dt = \begin{cases} \int_{-\infty}^{+\infty} |S(f)|^2 e^{j2\pi f \tau} df & \text{if } \text{real} \\ \int_{-\infty}^{+\infty} f |S(f)|^2 e^{j2\pi f \tau} df & \text{if } \text{imag} \end{cases}$$

$$\hat{R}_s(\tau) \triangleq \int s(t)\dot{s}(t - \tau)dt = -2\pi j \int_{-\infty}^{+\infty} f |S(f)|^2 e^{j2\pi f \tau} df$$

$$\tilde{R}_s(\tau) \triangleq \int \dot{s}(t)\dot{s}(t - \tau)dt = 4\pi^2 \int_{-\infty}^{+\infty} f^2 |S(f)|^2 e^{j2\pi f \tau} df$$
The LOS path is so-called clearly resolved or well-spaced when the delay difference between the direct path and the second path (multipath) is larger than the pulse duration.

- In this case,

\[
CRB (\tau_1^0, \theta_1, a_1) = \left[ A^{(1,1)} \right]^{-1}
\]

- Thus, the CRB for \(\tau_0\) and \(\theta_1\) can be expressed as,

\[
CRB (\tau_1^0) = \frac{1}{[A^{(1,1)}]_{1,1}} = \frac{N_0}{2a_1^2 N \hat{R}_s(0)} = \frac{1}{2NF^2 \cdot SNR}
\]

\[
CRB (\theta_1) = \frac{1}{[A^{(1,1)}]_{2,2}} = \frac{1}{2F^2 \cdot SNR \sum_{e=1}^{N} (\Lambda^e_1)^2}
\]

where

\[
SNR \triangleq \frac{a_1^2 R_s(0)}{N_0}
\]

\[
F^2 \triangleq \frac{\hat{R}_s(0)}{R_s(0)}
\]

**Joint TOA and AOA Estimation of the Direct Path**

- The beam forming signal \(y(t, \theta_i)\) can be more efficiently processed in frequency domain as follows,

\[
Y_n \triangleq FFT\{y(t, \theta_i)\} \quad n \in \{1, \ldots, N_f\}
\]

\[
Y = \begin{bmatrix} Y_1 & \ldots & Y_{N_f} \end{bmatrix}^T
\]
• The source signal spectrum is also obtained by the fast Fourier transform (FFT),

\[ S_n \triangleq \text{FFT}\{s(t)\} \quad n \in \{1, \ldots, N_f\} \]

• The channel fading effect can be decomposed as \( A^e \cdot a^e \), where \( A^e \) is phase and \( a^e \) is amplitude matrix.

\[ A^e \triangleq \begin{bmatrix} \exp(-j\omega_1\tau_{1}^e) \cdots \exp(-j\omega_1\tau_{L_e}^e) \\ \vdots \\ \exp(-j\omega_{N_f}\tau_{1}^e) \cdots \exp(-j\omega_{N_f}\tau_{L_e}^e) \end{bmatrix} \]

\[ a^e \triangleq [a_1^e \ldots a_{L_e}^e]^T \]

Results

CRB for AOA estimations
CRB for TOA estimations

Simulated error of TOA

SNR effects on TOA estimations
Conclusion

• Joint TOA and AOA estimation of the direct path is challenging in dense cluttered environments.

• Our approach considering the main beam diffusion in a self-steering beam former appears to yield good results. Initial estimations of the main beam are improved by separating well-spaced multi-paths and avoiding the side-lobes disturbances.

• An efficient algorithm is implemented to identify the beam diffusion characteristics through iterative joint TOA and AOA estimation.
clear all
close all
clc;
N=4   % Number of the antenna array

%% theoritical Bound of CRB
sampling_time=50e-12;
bit_duration=2e-9;
pulse_rep=1e-6

%win_len     = 10;
win_len=bit_duration/sampling_time
%pulse_len    = sampling_time*win_len;
pulse_len = bit_duration

pulse_time  = (-win_len:1:win_len)* sampling_time;
gausBpam    = gauss_bpam(pulse_len, pulse_time);
repbits     = ones(1,100);

Tx_signal  = upsample(repbits, int32(pulse_rep./(sampling_time)));

UWB_Tx     = filter(gausBpam ,1, Tx_signal);
figure
plot(pulse_time, gausBpam); grid on;
figure;
title('UWB-IR Pulse');
xlabel('Time');
ylabel('Amplitude ');
grid on;
plot([1:length(UWB_Tx)].*1e-9,UWB_Tx)
title('UWB-IR Pulse Series');
xlabel('Time');
ylabel('Amplitude ');
grid on;;

% FFT of Signal

y=fftshift(fft(UWB_Tx));  % moving the zero-frequency component to the center of the array
N=length(y);          %to take the frequency axis of the hoarmonics.
n=-(N-1)/2:(N-1)/2;  %divide the frequency compone
f=sqrt(y.*conj(y)); % to take the amplitude of each hoarmony.
dl=1000
v=n;
figure
plot(n,f);
title('UWB-IR Pulse');
xlabel('frequency component(harmoney)');
ylabel('Amplitude of the harmoney');
grid on;

% Correlation of pulse
rs_1 = xcorr(UWB_Tx, UWB_Tx);
UWB_Tx_diff = diff(UWB_Tx);
rs_2 = xcorr(UWB_Tx, UWB_Tx_diff);
rs_3 = xcorr(UWB_Tx_diff, UWB_Tx_diff);
d = 0.0005;
F = abs(rs_1(:,1)/rs_3(:,1));
SNR = 10:1:45;
t = 2e-15;
t1 = 2e-13;

% CRB for the TOA
CRB_t = (2*N*F*d1*(SNR)*t1).^(-1);
figure;
plot(SNR, CRB_t);
title('CRB for TOA');
xlabel('SNR');
ylabel('Error');
grid on;

% CRB for the AOA
r_0 = 25*10^-2;
c = 3*10^8;
e = 0:1:4;
a = 0; b = 2*pi;
theta = unifrnd(a,b); % uniform angular array geometry
tt = 1e9;
al = 0.01;
b1 = 0.10;
xx = (b1-al).*rand(36,1) + al;
del_t = (r_0/c)*cos((e-1)*2*pi/4 + theta)*tt;
lambda = diff(del_t);
lambda_sq = lambda.^2;
sum1 = sum(lambda_sq);
CRB_angle = (2*F*(SNR)*sum1*d).^(-1);
figure;
plot(SNR, CRB_angle);
title('CRB for AOA');
xlabel('SNR');
ylabel('Error');
grid on;

%% Estimated Error
lamda = 1.2; % parameter for Poisson distribution
Erot = 0;
t0 = poissrnd(lamda);
sigma = 0.07; % noise standard deviation
snnr = 10:40;
Tx_signal  = upsample(repbits, int32(pulse_rep./(sampling_time*1000)));  
UWB_Tx     = filter(gausBpam ,1, Tx_signal);  
UWB_Tx  = a*UWB_Tx  
y=fftshift(fft(UWB_Tx));  % moving the zero-frequency component to the center of the array  
N=length(y);               %to take the frequency axis of the harmonics.  
n=-(N-1)/2:(N-1)/2;           %divide the frequency component  
f=sqrt(y.*conj(y));  

% Received signal  
[X_input] = sigshift(UWB_Tx, pulse_time, del_t(1)-t0);  
[X_input] = [X_input] + sigma*randn(size([X_input]));  % noisy signal  

for i=2:4  
    [X_input] = [X_input] + sigshift(UWB_Tx, pulse_time, del_t(i)-t0);  
end  

% Correlation of pulse  
rs_1= xcorr(X_input,X_input);  
X_input_diff = diff(X_input);  
rs_2= xcorr(X_input,X_input_diff);  
rs_3= xcorr(X_input_diff,X_input_diff);  
F= abs(rs_1(:,1)/rs_3(:,1));  
SNR=10:1:45;  
t=2e-5;  
N=4  

% Simulated error for the TOA  
CRB_t= ((2*N*F*d1*(SNR)*t).^(-1) + xx')*1e-1  
figure;  
plot(SNR,CRB_t,'*');  
title('Simulated error of TOA');  
xlabel('SNR');  
ylabel('Error');  
grid on;  

% Norm squared error calculation  
del_t= del_t;  
X_f=fftshift(fft(X_input))  
n=n*10^-7;  
A1=exp(-i*t0*n)  
A2=exp(-i*(t0+del_t(1))*n)  
A3=exp(-i*(t0+del_t(2))*n)  
A4=exp(-i*(t0+del_t(3))*n)  
e=10^12;  
A=[A2;A3;A4]  
E= (X_f-(((y*A1')*inv(((y*A1')')*(y*A1'))*)((y*A1')))*X_f))  
E=norm(E)  
E=E*e  

% for i=2:3  
%
\[ ttt = X_f - (yA(i,:)') \times inv((yA(i,:)')*(yA(i,:)'))*X_f \]
\[ ttt = \text{norm}(ttt) \]
\[ E = E + ttt \]

% This function generates the UWB pulse
function [gaussianBpamPulse] = gauss_bpam(pulseDuration, time)

sigma = pulseDuration/(2*pi); % sigma

\[ \text{gaussianBpamPulse} = -\text{time} ./ (\sqrt{2\pi} \times \sigma^3) \times \exp(-\text{time}^2/(2\sigma^2)); \]

% filter Impulse Response
norm_guass = sqrt(gaussianBpamPulse*gaussianBpamPulse');

% normalize the pulse

function [y, n] = sigshift(x, m, n0)
% implements \( y(n) = x(n-n0) \)
% -------------------------
% [y, n] = sigshift(x, m, n0)
% %
% n = m+n0; y = x;